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Semiconductor Measurement Technology:

Permanent Damage Effects of Nuclear Radiation on the X-Band Performance of Silicon Schottky-Barrier Microwave Mixer Diodes

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Permanent Damage Effects of Nuclear Radiation
on the X-band Performance of
Silicon Schottky-Barrier Microwave Mixer Diodes

by

James M. Kenney

Abstract: The permanent damage induced by nuclear radiation in silicon Schottky-barrier X-band microwave mixer diodes was assessed by subjecting separate groups of diodes to ^{60}Co gamma rays and fast neutrons (E > 10 keV) of progressively higher levels, reaching a total gamma dose of 1.7×10^8 rads(Si) and a cumulative neutron fluence of 5.5×10^{15} cm^{-2}. Measurements were made at a local oscillator frequency of 9375 MHz to determine changes in conversion insertion loss, local oscillator return loss and SWR, i-f output conductance, self-bias, and forward current at one dc bias voltage.

No changes due to the gamma irradiation were observed. At a neutron fluence of 1.0×10^{15} cm^{-2}, changes in conversion insertion loss and forward current were just discernible. At 5.5×10^{15} cm^{-2}, the conversion insertion loss of most diodes was degraded by up to 0.7 dB, although some diodes were unchanged and the average change was only 0.2 dB. The return loss, SWR, and self-bias voltage of most diodes were distinctly altered at this level, and the forward current of all diodes was decreased. The i-f output conductance was not significantly altered.

A group of unirradiated diodes, intermixed with the gamma and neutron groups during measurements, served as a control. Since diode stability was recognized as an important factor, the three groups were matched on the basis of pre-irradiation conversion insertion loss stability. The three-sigma repeatability of the conversion insertion loss measurement was estimated from the control group measurements to be about 0.05 dB, with a systematic drift over the course of these measurements of about the same amount.

Key Words: Diodes; gamma rays; hardness assurance; microwave mixer diodes; mixers; neutrons; radiation hardness; receivers; Schottky-barrier diodes; semiconductors; solid-state devices; X-band measurements.

INTRODUCTION

Very little has been published concerning the radiation hardness of mixer diodes of any type.[1] Of the very limited number of measurement systems that have been constructed for the specialized area of microwave mixer diodes, almost all have been intended for production line testing. The limited precision expected of such systems would make them unsuitable for detecting small radiation-induced changes in diode characteristics or accurately measuring larger changes. Microwave mixer diode measurements have always been exceedingly difficult to perform with any great degree of accuracy or precision and there are still unsolved problems. Fortunately, these problems are of concern largely to absolute measurements and interlaboratory reproducibility, and therefore have little or no bearing on radiation hardness measurements, which only require good repeatability (low random uncertainty) and small systematic drift over the course of the measurements.

[1]Chaffin, F. J., *Microwave Semiconductor Devices: Fundamentals and Radiation Effects*, Chap. 6 (John Wiley & Sons, Inc., New York, 1973) provides the only previous data known to the present author.

The prime objective of this limited preliminary study was to determine if a significant problem existed in the radiation hardness (to permanent damage) of Schottky-barrier type microwave mixer diodes. A secondary objective was to provide data for better evaluation of the measurement system.

As a result of a study originally funded by the Navy, there was in operation at NBS an X-band mixer measurement system[2] which was ideally suited for the detection of very small changes in a number of important characteristics. In cooperation with the Harry Diamond Laboratories, at whose facilities the diodes were irradiated, an investigation was performed at NBS to ascertain the effects of gamma rays and fast neutrons on samples of four brands (and two grades) of Schottky-barrier mixer diodes.

EXPERIMENTAL FACILITIES AND PROCEDURES

Samples were procured of every brand of Schottky-barrier X-band mixer diode on the market with case dimensions allowing physical interchangeability with the type 1N23 point-contact X-band mixer diode, for which suitable holders were available. These were all unbonded silicon diodes. The microwave parameters measured are not a function of the diode alone, but depend also upon the structure of the holder in which the diode is mounted (providing definable and isolated input and output terminals). They also depend upon the immittances terminating the holder, and the available local oscillator power. For the 1N23 type, a standard fixed-tuned holder has been designated by MIL specifications, the drawings for which are available from the Defense Electronics Supply Center.[3] Three holders made to these specifications had been obtained commercially but only one (Serial 103) was used for the microwave measurements. It is understood that this holder type, or the tunable type it replaces (nominally identical for 1N23 measurements when properly tuned), is also used by the diode manufacturers when testing the Schottky-barrier diode types used in this study.

A detailed description and analysis of the X-band measurement system used in this study is given elsewhere.[2] Only a brief discussion will therefore be presented here.

The NBS X-band mixer measurement system in its present state can be used to measure: conversion insertion loss (conversion loss uncorrected for i-f load mismatch); directly measured conversion loss (with i-f mismatch taken into account)[4]; local-oscillator mismatch magnitude, expressed as return loss or as standing wave ratio (SWR); i-f output conductance, expressed as its reciprocal (traditionally but erroneously referred to as "i-f impedance"); self-bias voltage (rectified local-oscillator current through a 100-Ω dc load resistance); and forward current at a selected forward voltage (static dc conductance with the rf switched off).

The most important measurements, and the most difficult to perform, were those of conversion insertion loss. These measurements were made by an improved incremental modulation method, using a rotary-vane attenuator modified by the addition of adjustable precision stops. Three micrometer-head stops were used, permitting independent adjustment of the attenuation required to establish (in rapid sequence) three power levels, corresponding to (1) the

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[2]Kenney, J. M., *Semiconductor Measurement Technology:* Modulation Methods for Microwave Mixer Measurements of Standards Quality, NBS Special Publication 400-16 (in preparation).

[3]Defense Electronics Supply Center, Dayton, Ohio 45401, Drawing List D65019, Diode Test Holder — Model 1181-R1, 9.375 GHz (X-band).

[4]There are good reasons for not making this correction, although required by the definition of conversion loss. The i-f mismatch is not generally eliminated by tuning in field use, so that conversion insertion loss is a more realistic parameter. Conversion insertion loss is also easier to compute, since it may be read from a one-dimensional table of loss versus mixer output voltage, whereas conversion loss requires an additional correction for mismatch factor, using i-f output conductance, or the use of a two-dimensional table of loss versus mixer output voltage and i-f conductance (impractical for high precision), or an individual calculation for each measurement.

nominal local oscillator power specified for the measurement, (2) the crest (maximum) value of power that would result from sinusoidal modulation of the local oscillator, and (3) the trough (minimum) value of power for the same modulation. The total attenuation range (set at 1 dB for this study) therefore corresponds to the crest-to-trough power ratio for the equivalent sinusoidal modulation. This power ratio in turn establishes the modulation factor and the side-band amplitude that would result from such a modulation of a given nominal local oscillator (carrier) power (1 mW for this study).

Conversion insertion loss is the ratio of the available input signal power at a single frequency to the delivered output signal power at a single frequency. The input signal power was calculated from the side-band amplitude of the equivalent sinusoidal modulation, and the output signal power was calculated from the peak-to-peak i-f output voltage, taking into account the linear addition of output voltages corresponding to the two sidebands. The i-f output voltage peaks were the minimum and maximum values of the total mixer output voltage (i-f + dc) corresponding to the crest and trough settings of the modulation attenuator, and were thus read as dc voltages. The use of a bilateral increment, i.e., one where the power is varied appropriately both above and below the nominal local oscillator power, tends to yield better mixer linearity than a unilateral (one-sided) increment of the same magnitude, since the latter would require twice the excursion from the nominal local oscillator power, which is equivalent to using four times the signal power.

A tuned reflectometer was used to obtain the return loss (from which the SWR was calculated), and a recently reinvented load perturbation technique (Mance's method — of nineteenth century origin) was used to obtain the reciprocal of i-f output conductance, using as a signal the same incremental output voltage as in the conversion loss measurement. Digital voltmeters were used to indicate the mixer output voltages, the voltages associated with the precision bolometric measurements used to establish the nominal local oscillator power, and the voltage from a thin-film thermocouple ("dry calorimeter") used to monitor this r-f power.

The frequency and amplitude of the local oscillator were well stabilized by phase-lock and leveling circuits incorporating the best available components.

Forward current at a selected forward voltage was obtained by a minor modification of the i-f/dc output circuit, which incorporated a constant-current source set to equal the mixer output current for the purpose of establishing distinct dc and i-f loads (100 Ω and 400 Ω, respectively) at essentially a zero intermediate frequency. Unfortunately, this modification (unplugging a decade resistance box) did not permit the current to be set as the independent variable. The current was calculated from the voltage drop across the diode and across the series combination of the diode and a 100-Ω resistor. For the first measurements of some diodes, the current was left as set during the microwave measurements, but the resulting irrational values of voltage were tedious to reset during subsequent measurements, so that the voltage values were readjusted to the nearest multiple of 50 mV. It was thought that a current about equal to that used in the microwave measurements was the largest that should be used, to avoid significant diode heating with attendant drift and possible burnout; the measurement of much smaller currents would have been less precise. It was therefore not possible to use a common voltage for all diodes, as this would have resulted in widely different currents. In retrospect, a more extensive modification to permit setting the current and measuring the diode voltage would have been preferable.

In addition to the measurements made with the microwave system, all diodes were measured at a number of bias points to determine their I-V and C-V characteristics, using semiautomatic equipment for the former, and a 1 MHz three-terminal capacitance bridge for the latter. Unfortunately, time did not permit analysis of these data, and transients produced by the semiautomatic I-V equipment altered or destroyed some diodes, as will be discussed.

A qualitative study of the I-V characteristics was made using curve-tracer photographs taken before and after irradiation. Even this equipment was seen to occasionally alter the diode characteristics (generally to improve them, and generally only very slightly, however).

The most important single mixer parameter is standard overall average noise figure, which is a measure of the degradation of receiver front-end signal-to-noise ratio by the mixer. No noise measurements were made for this study, but the principal contributor to standard

overall average noise figure is conversion loss. These parameters are related by the expression

$$\overline{F}_{os} = L(N + \overline{F}_{is} - 1)$$

where $\overline{F}_{os}$ = standard overall average noise figure,

L = conversion loss,

N = output noise ratio ($\approx$ 1 for Schottky-barrier diodes), and

$\overline{F}_{is}$ = standard i-f average noise figure (specified as $\log^{-1} 0.15$ for these and most other mixer diode types);

all terms being power ratios.

Expressed in decibels, $\overline{F}'_{os}$ (= 10 log $\overline{F}_{os}$) is therefore larger than L'(= 10 log L) by close to a constant 1.5 dB. A closer approximation of N for these diode types, based upon measurements made at an intermediate frequency of 30 MHz, is 1.1,[5] making the difference between $\overline{F}'_{os}$ and L' about 1.8 dB. The small contribution by the excess output noise ratio (N - 1) of only about 0.3 dB is far outweighed by the conversion loss contribution of more than about 4.5 dB, as measured for the diodes used in this study.

The 54 diodes used in this study (reduced to 51 by accidental loss) were culled from a total of 90 diodes obtained from four different manufacturers, and were of two grades: 6.0 dB and 6.5 dB maximum standard overall average noise figure. Each of these 90 diodes was measured at least twice to establish their stability, since it was recognized that some diodes were much less stable than others and that diode instability was a significant factor in measurement repeatability (random uncertainty). Only those diodes with conversion insertion loss less than 6.0 dB for these pre-irradiation measurements, and with a change of less than 0.1 dB between successive measurements, were accepted for the study. Because the 90 diodes were received over a period of time, they were grouped into two lots. The first lot diodes were measured at least six times: twice before irradiation and once after each of four irradiations. The second lot diodes were measured three times: twice before irradiation and once after a single irradiation. Each lot was divided into three equal sized groups, with all brands and grades equally represented. This division was done in such a way that the groups were approximately equal in average diode stability. After the groups were assembled they were randomly labeled for gamma irradiation, for neutron irradiation, and to serve as a control.

The diodes from the three groups were measured in a fixed sequence: a gamma group diode, followed by a control group diode, followed by a neutron group diode, the cycle then being repeated. By following this sequence it was thus assured that a control group diode would be measured at nearly the same time as both a gamma group diode and a neutron group diode, so that systematic drift would tend to affect all groups equally. Interruptions in measurement runs were permitted only after every third measurement, i.e., between a neutron group diode measurement and the following gamma group diode measurement. The control group thus served equally well to control both the gamma group and the neutron group. All microwave measurements were made at a local oscillator frequency of 9375 MHz, the standard X-band diode frequency originally established for the point-contact 1N23.

A calibrated bolometer was substituted for the diode holder prior to each measurement run to establish the calorimeter voltage corresponding to exactly 1 mW of available local oscillator power. The calorimeter was used in resetting the power immediately prior to each diode measurement. Before making the power check and measurement, the diode was allowed to stabilize for several minutes to insure thermal equilibrium. The ambient temperature was controlled to within about ±0.2°C. The temperature was recorded at the start of each diode measurement and during each power calibration measurement, using a thermometer in contact with the aluminum base plate to which the waveguide was clamped. After experience indicated the importance of temperature stability, a second thermometer, thermally insulated from the

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[5]From discussions with diode production engineers.

base plate, was used to indicate the air temperature; measurements were made only when the two thermometers agreed to within ±0.2°C, to minimize thermal gradients and rapid temperature changes.

Because of axial asymmetry, detectable as output voltage changes when the diode is rotated in the holder (probably due to the whisker bend), the angular orientation of the diode in the holder was always kept the same each time it was reinserted. The end caps, which were removed before irradiation, were marked to permit their reattachment in the same orientation as before, to guard against the possibility of changing any cap asymmetry.

Table 1 lists the cumulative radiation levels used and the numbers assigned to the subsequent measurements. Measurements 1 and 2 were the last two pre-irradiation measurements (the only two for many diodes).

RESULTS AND ANALYSIS

Results of the pre-irradiation measurements used to cull the defective and unstable diodes are summarized in table 2. Several such measurements were made at first, but these were later reduced to two. The samples of brand A diodes were found to be particularly unstable, even though handled with the greatest care, and their characteristics could be altered by the slightest mechanical shock, such as the rotation of a waveguide switch audibly against its stop (even with rigid clamping of the waveguide between the switch and holder). Compare the reduction in the number of measurable diodes on subsequent measurements with those of brand B, which were intermixed with those of brand A during measurement runs. Some brand A diodes exhibited an output voltage too unstable to record, and were therefore rejected. The samples of brand D diodes were unusually susceptible to electrical transients, as most were radically altered when all diodes were measured for static characteristics using semiautomatic equipment. Three brand A diodes (one from each group) were destroyed by this equipment, but this was found to be due to a slight alteration in measurement sequence from that used in preliminary testing (using expendable diodes), which intensified the transients. The samples of brand C diodes, while reasonably stable, had notably inferior conversion loss compared to those of other brands, even those of 0.5 dB lower grade. (A change in conversion loss results in the same change in overall average noise figure when both are expressed in decibels, if the output noise ratio and i-f average noise figure remain constant.)

A statistical analysis of all data is given in tables 3 through 8. A behavioral history of each characteristic of each diode in the first lot is given in figures 1 through 6, where the letter in the diode designation is the brand code. Primes are used for the 6.5 dB diodes, to distinguish them from the 6.0 dB types. From these figures, it may be seen that the last neutron irradiation caused noticeable changes in the conversion insertion loss, return loss, SWR, self-bias voltage, and forward current of most diodes, whereas i-f output conductance seems unaffected. There were only two diodes for which no microwave characteristic was significantly altered by the final neutron irradiation: C4 and C9. (The conversion insertion loss of diode C9 was possibly degraded somewhat, but the change was sufficiently small that it could reasonably have been due to random error.) The conversion insertion loss of only two other diodes (B1 and B10) was unaffected. The return loss and SWR of no diodes other than C4 and C9 were unaffected. The self-bias voltage of only one other diode (B1) was unaffected. The forward current of all diodes was significantly altered by the neutrons; even the next to last neutron irradiation seems to have affected some diodes. This next-to-last irradiation also seems to have had a slight affect on the conversion loss, return loss, and SWR of some diodes, although these changes appear nonrandom chiefly because of the subsequent larger changes due to the last irradiation. Over the last two irradiations, the largest conversion insertion loss change in a neutron-group diode was 0.69 dB, and the average change was only 0.20 dB.

The gamma group seems to have been affected little, if at all, at any radiation level.

The lot 2 statistics were strongly affected by the presence of grossly atypical diodes, probably due to handling. Disregarding one or two of the largest changes in characteristics from all three groups enables a better comparison of the more typical diode behavior. In most cases, the diodes exhibiting the largest changes in one characteristic exhibited large changes in the other characteristics.

While the characteristics studied were only moderately affected by a neutron fluence of 5.5×10^{15} cm^{-2}, it is possible that reverse current increases causing increased output noise ratios would have made the changes in overall average noise figure larger than the observed changes in conversion loss.

It was originally believed that no substantial change in the static (I-V) characteristics of a diode could take place without a noticeable affect on the observed microwave characteristics. For example, since self-bias voltage is the dc component of the rectified local oscillator current multiplied by the 100-Ω dc load resistance, any change in static characteristics should alter the rectification efficiency and therefore change the self-bias. Conversion loss and the input and output immittance parameters also depend, in different ways, upon the static characteristics. Diodes C4 and C9, however, exhibited little or no change in microwave characteristics following exposure to a neutron fluence of 5.5×10^{15} cm^{-2}, and diodes B1 and B10 were largely unaffected except in return loss and SWR, despite forward current reductions similar to the other diodes. The possibility must therefore be considered that significant changes may have occurred in the reverse conduction of some diodes, increasing the output noise ratio with little or no disturbance to the other microwave characteristics. While this is most likely to have occurred, if at all, at the 5.5×10^{15} cm^{-2} level, the slight forward current reductions at 1.0×10^{15} cm^{-2} indicate possible noise increases at the latter level.

That such noise changes probably did not occur for most diodes is indicated by table 9, which was prepared from comparison of the photographs of the diode I-V characteristics before the first irradiation and after the final irradiation. Both lots are combined for these comparisons. It can be seen that the reverse current definitely increased in only 5 of the 17 neutron group diodes and in none of the gamma group diodes. The true number could be somewhat greater, since changes in the reverse breakdown characteristics, as the reverse voltage was increased, was occasionally observed in the course of taking the post-irradiation photos. Most of these changes tended to sharpen the breakdown, reducing the reverse current.

Examination of the plots of conversion insertion loss mean in figure 1 (broken lines) reveals appreciable systematic shifts between the second and third measurements of roughly the same magnitude in all groups. This obviously systematic change, of unknown origin, must be eliminated when evaluating "short-term" repeatability (the usual meaning of repeatability). Except for small random changes due to the finite number of diodes, the control group mean should be a constant for all measurements. The control group data can be corrected to achieve this by adding to each datum the difference between the overall mean (the mean of the six measurement means) and the mean for the particular measurement. This correction may be expected to cause a small but probably negligible reduction in the random variability, since the correction includes a small part of the random change in the datum being corrected.

Making this correction for all control group conversion insertion loss data and then recalculating the statistics resulted in significant improvements. The mean sample standard deviation was reduced from 0.033 dB to 0.018 dB. The sample standard deviation of the nine sample standard deviations remained essentially unchanged, 0.008 dB against the previous 0.009 dB. The range of 0.025 dB to 0.051 dB was shifted downward and somewhat reduced, becoming 0.007 dB to 0.030 dB, and the median sample standard deviation was reduced from 0.031 dB to 0.019 dB. How much of the remaining random uncertainty is due to diode changes and how much to measurement (equipment plus operator) variability is unknown, but a three-sigma uncertainty of 0.05 dB can be assigned as a reasonable estimate of the latter. An additional 0.05 dB can be assigned as a tentative limit on long-term systematic drift, if system calibrations are unchanged, although the shift between measurements 1 and 2 suggests the possibility of occasional larger changes, perhaps from a different cause. Only additional experience over a much longer period could establish reliable limits on long-term drift.

CONCLUSIONS

The samples of unbonded X-band microwave silicon Schottky-barrier mixer diodes were essentially unaffected by ^{60}Co gamma rays up to and including 1.7×10^{8} rads(Si) and fast neutrons (E > 10 keV) up to and including a fluence of 1.0×10^{15} cm^{-2}. The observed effects

of a neutron fluence of 5.5×10^{15} cm^{-2} were sufficiently small as to permit continued system operation with, at worst, only a moderate reduction in performance.[6]

Appreciable radiation hardness differences were observed. In particular, neither of the neutron-bombarded diodes of one brand exhibited significant microwave characteristic changes after exposure to 5.5×10^{15} cm^{-2}. This was not true of any other diodes, although some characteristics of some other diodes seemed unaffected. The number of diodes of the apparently more hardened brand was too limited, however, to permit a firm conclusion that brand differences exist.

Incidental to the purpose of this investigation, but of significance to the users of these diodes, are the observations that many diodes of one brand were very susceptible to shock and vibration, even during careful handling, and that those of another brand were very susceptible to electrical transients. On the basis of the measured samples, wide differences seem to exist between brands with regard to their average parameter values, despite identical specifications.

As presently constructed, the available unbonded X-band Schottky-barrier microwave mixer diodes may reasonably be considered to be adequately hard at the radiation levels used in this study, with the possible exception of 5.5×10^{15} neutrons per square centimeter. Full assurance of satisfactory performance at the higher radiation levels of particular types and brands of diodes would require individual testing, since it is apparent from the results of this study that there are appreciable variations in the effects of radiation on diodes of the same manufacture, and a strong indication that brand-correlated variations may exist as well. In the absence of adequate modeling to quantitatively explain the radiation-induced changes noted in this empirical study, Schottky diodes of different designs, such as the bonded types, cannot be assumed to have the same radiation sensitivity. Such modeling would be very difficult, due to the complex nature of mixers. For critical systems application, therefore, the radiation hardness of different types of Schottky diodes should be determined on a type-by-type, brand-by-brand, and perhaps even on a batch-to-batch basis until there is sufficient experience developed to permit a greater generalization.

Radiation-hard diodes are of little benefit to critical systems if these diodes are susceptible to even more likely failure modes, or if they have inferior performance when installed. Adequate testing for resistance to shock, vibration, and burnout are required. An even more basic requirement is that adequate attention be given to measurement uncertainties, in order to reduce variations in initial performance between diodes of the same nominal type and grade, inconsistencies between diodes of the same type but of different grades, and differences between different type diodes of the same nominal specification limits. This calls for greater measurement precision in the grading process, and better standards within and between manufacturing plants.

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[6]These results are in rough agreement with measurements cited by Chaffin, *op. cit.* (figure 6.21), for one of three types of Schottky diodes measured (apparently with quite limited precision) at a local-oscillator frequency of 250 MHz. This type, however, was unpassivated (no oxide), a design unlikely to have been used for the microwave types measured in the present study. Of the other two types measured by Chaffin, one exhibited far larger neutron-induced changes than any of the microwave diodes studied here while the other was apparently unaffected to within the limited measurement precision.

Table 1. Cumulative Radiation Levels*

Lot	Designation of Measurement Following Irradiation	^{60}Co Gamma Ray Dosage rads(Si)	High Energy (E > 10 keV) Total Neutron Fluence cm^{-2}
1	3	1.0×10^{6}	1.0×10^{13}
1	4	1.1×10^{7}	1.1×10^{14}
1	5	5.1×10^{7}	1.0×10^{15}
1	6	1.7×10^{8}	5.5×10^{15}
2	3	1.6×10^{8}	5.4×10^{15}

*These radiation levels were selected by N. Berg of the Harry Diamond Laboratories, who also supervised the irradiations. The neutrons were obtained from the TRIGA type reactor at the HDL facilities.

Table 2. Conversion insertion loss repeatability by brand and lot prior to selection of diodes for experimental groups. Each lot initially consisted of ten diodes of a particular brand and grade received together. Lot 2 diodes were subsequently handled separately from lot 1 diodes.

Supplier Brand Code	Diode Grade (dB)	Lot	No. of Initial Failures	Measurement Repetition	No. of Measurable Diodes	Mean Change (dB)	Smpl. Std. Dev. of Changes (dB)
A	6.0	1	1	1	9	-0.058	0.105-
A	6.5	1	2	1	7	0.011	0.172
				2	4	-0.100	0.218
				3	2	-0.139	0.113
A	6.5	2	1	1	8	-0.032	0.098
B	6.0	1	0	1	10	0.009	0.032
B	6.5	1	0	1	9	0.001	0.040
				2	9	0.019	0.051
				3	9	-0.038	0.030
B	6.5	2	1	1	9	-0.024	0.021
C	6.0	1	2	1	8	-0.004	0.027
C	6.5	2	1	1	9	-0.071	0.026
D	6.5	2	1	1	9	-0.092	0.371

Table 3A. Lot 1 Group Statistics (9 Diodes Per Group)
Conversion Insertion Loss (Decibels)

Measurement	1	2	3	4	5	6
Median						
Gamma Group:	5.246	5.223	5.193	5.183	5.186	5.166
Control Group:	4.868	4.793	4.744	4.752	4.768	4.737
Neutron Group:	5.050	4.982	4.959	4.962	5.146	5.144
Pooled:	5.050	5.009	4.988	5.040	5.146	5.163
Mean						
Gamma Group:	5.197	5.194	5.112	5.136	5.147	5.143
Control Group:	5.065-	5.053	4.997	5.013	5.010	5.001
Neutron Group:	5.052	5.047	4.986	4.992	5.025+	5.191
Pooled:	5.105-	5.098	5.032	5.047	5.061	5.112
Sample Standard Deviation						
Gamma Group:	0.318	0.308	0.321	0.326	0.324	0.318
Control Group:	0.457	0.468	0.470	0.484	0.475-	0.474
Neutron Group:	0.373	0.368	0.389	0.382	0.392	0.389
Pooled:	0.378	0.378	0.387	0.392	0.391	0.392
Mean Change from Previous Measurement						
Gamma Group:		-0.003	-0.082	0.024	0.012	-0.003
Control Group:		-0.012	-0.056	0.016	-0.003	-0.010
Neutron Group:		-0.005-	-0.061	0.006	0.034	0.166
Pooled:		-0.007	-0.066	0.015+	0.014	0.051
Sample Standard Deviation of Changes from Previous Measurement						
Gamma Group:		0.041	0.054	0.026	0.042	0.047
Control Group:		0.034	0.019	0.023	0.022	0.034
Neutron Group:		0.040	0.062	0.025-	0.087	0.178
Pooled:		0.037	0.048	0.025-	0.057	0.133

Table 3B. Lot 2 Group Statistics (8 Diodes Per Group)
Conversion Insertion Loss (Decibels)

Measurement	1	2	3	3*	3**
Median					
Gamma Group:	4.952	4.958	4.963		
Control Group:	4.896	4.865	5.032		
Neutron Group:	5.043	5.028	5.216		
Pooled:	4.953	4.958	5.068		
Mean					
Gamma Group:	5.123	5.093	5.116		
Control Group:	4.968	4.940	5.024		
Neutron Group:	5.157	5.122	5.242		
Pooled:	5.083	5.052	5.127		
Sample Standard Deviation					
Gamma Group:	0.487	0.468	0.462		
Control Group:	0.251	0.228	0.249		
Neutron Group:	0.508	0.507	0.457		
Pooled:	0.421	0.409	0.395-		
Mean Change from Previous Measurement					
Gamma Group:		-0.030	0.023	0.007	0.018
Control Group:		-0.028	0.071	0.013	0.022
Neutron Group:		-0.035	0.120	0.093	0.065+
Pooled:		-0.031	0.072	0.038	0.035
Sample Standard Deviation of Changes from Previous Measurement					
Gamma Group:		0.041	0.055-	0.035-	0.023
Control Group:		0.033	0.170	0.036	0.027
Neutron Group:		0.043	0.126	0.108	0.086
Pooled:		0.038	0.127	0.076	0.055+

*Excluding largest datum from each group
**Excluding two largest data from each group

Table 4A. Lot 1 Group Statistics (9 Diodes Per Group)
Local Oscillator Return Loss (Decibels)

Measurement	1	2	3	4	5	6
Median						
Gamma Group:	14.7	14.6	15.0	15.2	15.4	15.2
Control Group:	14.6	14.4	14.8	14.9	14.7	14.8
Neutron Group:	16.0	15.8	16.0	16.2	16.6	18.7
Pooled:	14.7	14.6	15.0	15.0	15.0	15.7
Mean						
Gamma Group:	14.4	14.3	14.5	14.7	14.8	15.2
Control Group:	16.6	16.4	16.7	16.5	16.5	16.5
Neutron Group:	17.8	18.5	17.1	17.3	17.1	18.3
Pooled:	16.2	16.4	16.1	16.2	16.2	16.7
Sample Standard Deviation						
Gamma Group:	4.8	4.7	5.0	5.2	5.3	5.8
Control Group:	7.6	7.3	7.5	7.2	7.4	7.3
Neutron Group:	8.4	10.1	6.7	6.8	6.3	6.0
Pooled:	6.9	7.6	6.3	6.3	6.2	6.3
Mean Change from Previous Measurement						
Gamma Group:		-0.1	0.3	0.2	0.1	0.4
Control Group:		-0.2	0.3	-0.1	-0.1	-0.1
Neutron Group:		0.7	-1.4	0.2	-0.1	1.2
Pooled:		0.1	-0.3	0.1	0.0	0.5
Sample Standard Deviation of Changes from Previous Measurement						
Gamma Group:		0.2	0.4	0.3	0.2	0.8
Control Group:		0.4	0.4	0.3	0.2	0.1
Neutron Group:		2.0	4.1	0.5	0.8	2.6
Pooled:		1.2	2.4	0.4	0.5	1.6

Table 4B. Lot 2 Group Statistics (8 Diodes Per Group)
Local Oscillator Return Loss (Decibels)

Measurement	1	2	3	3*	3**
Median					
Gamma Group:	16.0	16.0	16.0		
Control Group:	14.8	14.8	14.9		
Neutron Group:	13.6	13.0	13.6		
Pooled:	14.8	14.8	14.9		
Mean					
Gamma Group:	14.6	14.5	14.7		
Control Group:	15.3	14.8	14.4		
Neutron Group:	13.5	13.4	14.3		
Pooled:	14.5	14.2	14.5		
Sample Standard Deviation					
Gamma Group:	4.4	4.3	4.3		
Control Group:	4.0	3.3	2.4		
Neutron Group:	4.2	4.2	5.2		
Pooled:	4.1	3.8	4.0		
Mean Change from Previous Measurement					
Gamma Group:		-0.1	0.2	0.1	0.2
Control Group:		-0.5	-0.4	-0.1	0.2
Neutron Group:		-0.1	0.9	0.4	0.9
Pooled:		-0.2	0.2	0.1	0.5
Sample Standard Deviation of Changes from Previous Measurement					
Gamma Group:		0.5	0.5	0.4	0.2
Control Group:		1.1	1.3	0.9	0.4
Neutron Group:		0.6	1.8	1.3	0.5
Pooled:		0.7	1.4	0.9	0.5

*Excluding largest datum from each group
**Excluding two largest data from each group

Table 9. Changes in I-V Characteristics Observed for Curve-Tracer Photos

Forward Current Changes	Number of Diodes: Gamma Group	Control Group	Neutron Group
+++ Pronounced increase	0	0	2
++ Small but definite increase	0	0	3
+ Barely discernible increase*	4	7	0
No discernible change	9	8	3
- Barely discernible decrease*	4	2	1
-- Small but definite decrease	0	0	8
--- Pronounced decrease	0	0	0

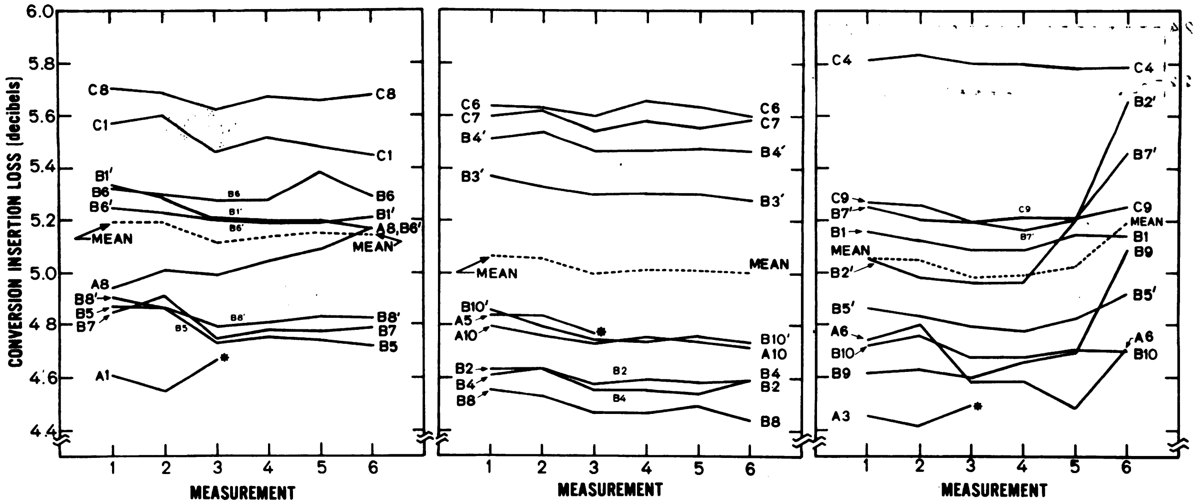
Reverse Current Changes	Number of Diodes: Gamma Group	Control Group	Neutron Group
+++ Pronounced increase	0	1	2
++ Small but definite increase	0	0	3
+ Barely discernible increase*	3	6	0
No discernible change	5	9	3
- Barely discernible decrease*	5	1	1
-- Small but definite decrease	4	0	8
--- Pronounced decrease	0	0	0

*Possibly due to measurement error.

Table 10. Repeatability of Control Group
(9 Diodes, 6 Measurements of Each)

	Mean of Means	S.S.D.* of 6 Means	Mean of 9 S.S.D.'s	Range of 9 S.S.D.'s	S.S.D. of 9 S.S.D.'s
Conversion Loss (dB)	5.023	0.029	0.033	0.024-0.051	0.009
			0.018**	0.007-0.030**	0.008**
L.O. Return Loss (dB)	16.5	0.1	0.2	0.0-0.5	0.2
L.O. Standing Wave Ratio	1.51	0.01	0.01	0.00-0.02	0.01
I.F. Output Cond. Rec. (ohms)	358	1	2	1-3	1
Self-Bias Voltage (mVDC)	159.9	0.2	0.3	0.1-0.7	0.2
Forward Current (mADC)	1.624	0.007	0.012	0.002-0.036	0.13

*Sample Standard Deviation
**After correcting for systematic drift by subtracting from each datum the difference between the mean for the particular measurement and the overall mean of 5.023 dB. (Contribution to variance in mean by datum being corrected is neglected.) These corrections ranged between -0.026 dB and 0.042 dB, and were largely required by an unexplained shift between measurements 2 and 3 which is obvious from the conversion loss plots (Figures 1A through 1C).



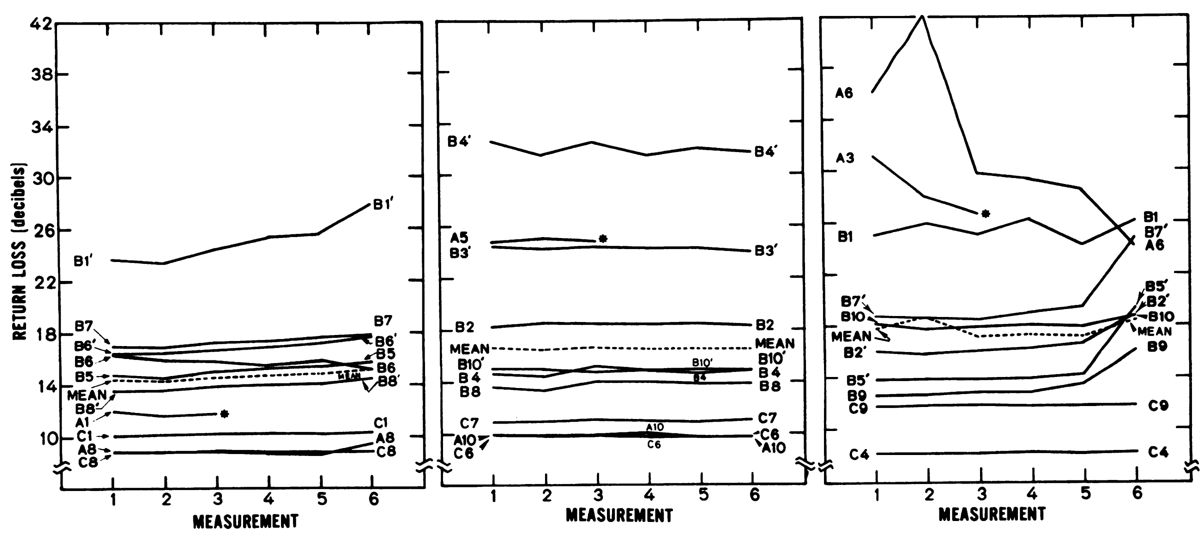
a. Gamma Group

b. Control Group

c. Neutron Group

Figure 1. Conversion Insertion Loss (Decibels)

* diode accidently destroyed (not included in mean)



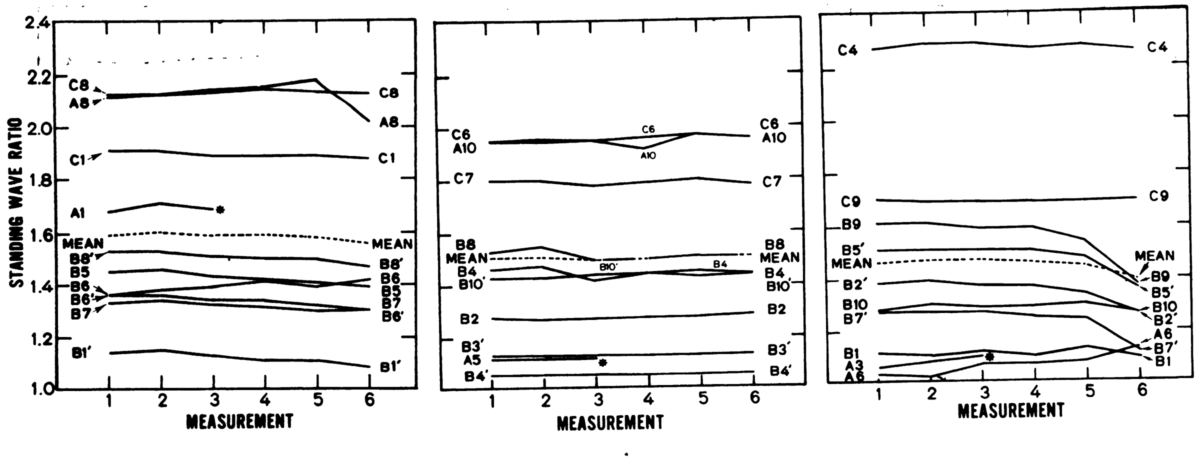
a. Gamma Group

b. Control Group

c. Neutron Group

Figure 2. Return Loss (Decibels)

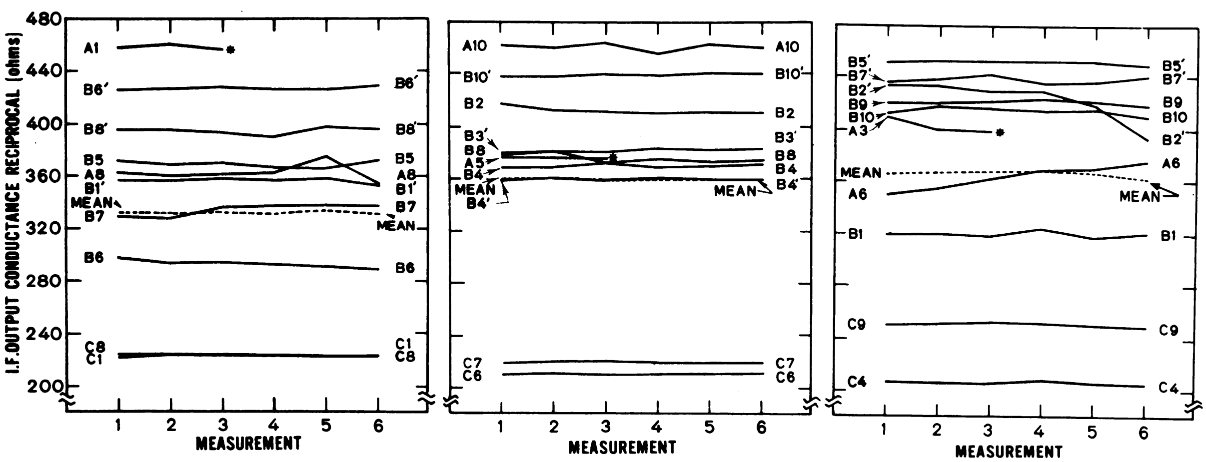
* diode accidently destroyed (not included in mean)



a. Gamma Group b. Control Group c. Neutron Group

Figure 3. Standing Wave Ratio

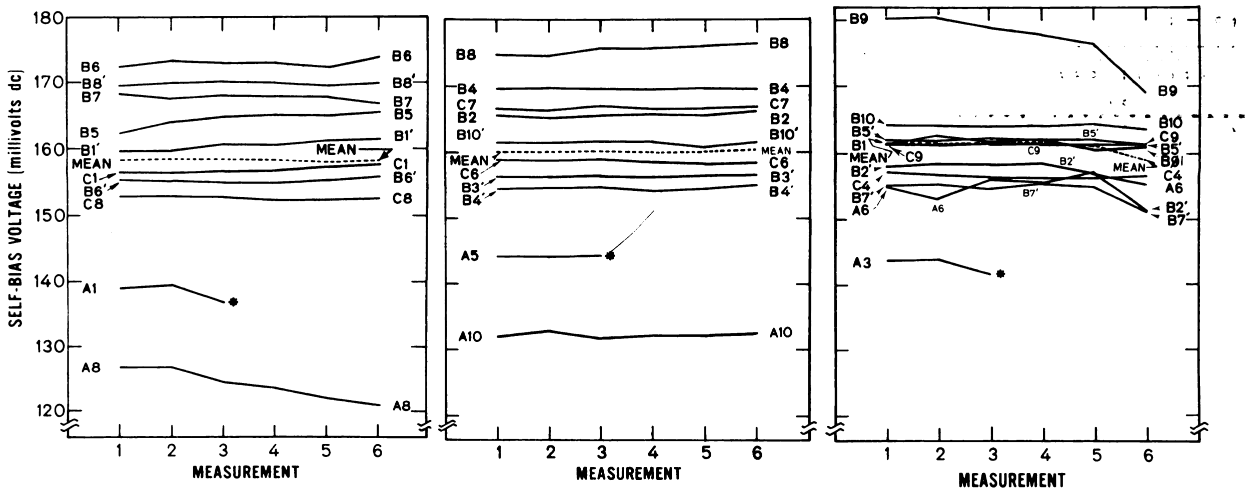
* diode accidently destroyed (not included in mean)



a. Gamma Group b. Control Group c. Neutron Group

Figure 4. Reciprocal of I-F Output Conductance (Ohms)

* diode accidently destroyed (not included in mean)



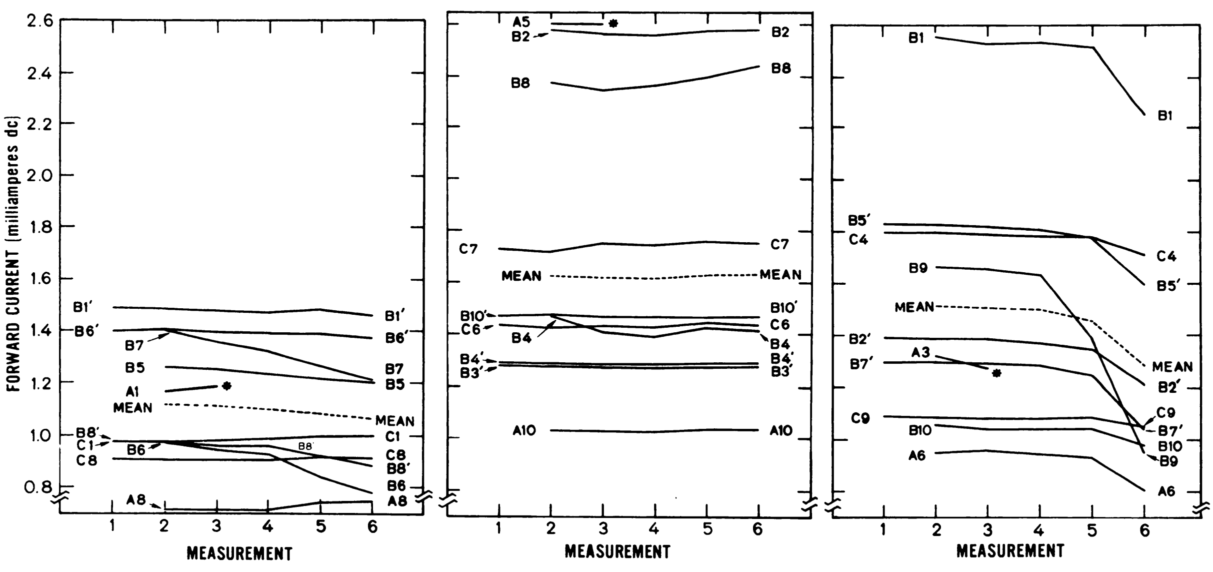
a. Gamma Group

b. Control Group

c. Neutron Group

Figure 5. Self-Bias Voltage (Millivolts dc)

* diode accidently destroyed (not included in mean)



a. Gamma Group

b. Control Group

c. Neutron Group

Figure 6. Forward Current (Milliamperes dc)

* diode accidently destroyed (not included in mean)

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The permanent damage induced by nuclear radiation in silicon Schottky-barrier X-band microwave mixer diodes was assessed by subjecting separate groups of diodes to ^{60}Co gamma rays and fast neutrons (E>10 keV) of progressively higher levels, reaching a total gamma dose of 1.7×10^8 rads(Si) and a cumulative neutron fluence of $5.5 \times 10^{15} cm^{-2}$. Measurements were made at a local oscillator frequency of 9375 MHz to determine changes in conversion insertion loss, local oscillator return loss and SWR, i-f output conductance, self-bias, and forward current at one dc bias voltage.

No changes due to the gamma irradiation were observed. At a neutron fluence of $1.0 \times 10^{15} cm^{-2}$, changes in conversion insertion loss and forward current were just discernible. At $5.5 \times 10^{15} cm^{-2}$, the conversion insertion loss of most diodes was degraded by up to 0.7 dB, although some diodes were unchanged and the average change was only 0.2 dB. The return loss, SWR, and self-bias voltage of most diodes were distinctly altered at this level, and the forward current of all diodes was decreased. The i-f output conductance was not significantly altered.

A group of unirradiated diodes, intermixed with the gamma and neutron groups during measurements, served as a control. Since diode stability was recognized as an important factor, the three groups were matched on the basis of pre-irradiation conversion insertion loss stability. The three-sigma repeatability of the conversion insertion loss measurement was estimated from the control group measurements to be about 0.05 dB, with a systematic drift over the course of these measurements of about the same amount.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Diodes; gamma rays; hardness assurance; microwave mixer diodes; mixers; neutrons; radiation hardness; receivers; Schottky-barrier diodes; semiconductors; solid-state devices; X-band measurements.

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